Outline

- Background and objectives
- Nozzle overview and ground test results
- Flight test approach and pilot-vehicle interface
- Flight test execution and results
- Concluding remarks

Hi, I am Major Greg Johnson and I'm the US Air Force project pilot on the team. So far we've covered the purpose of ACTIVE, some details about the nozzles, and our overall test approach. I'm going to wrap it up with a description of our flight test techniques, some initial results, and where we intend to go from here.

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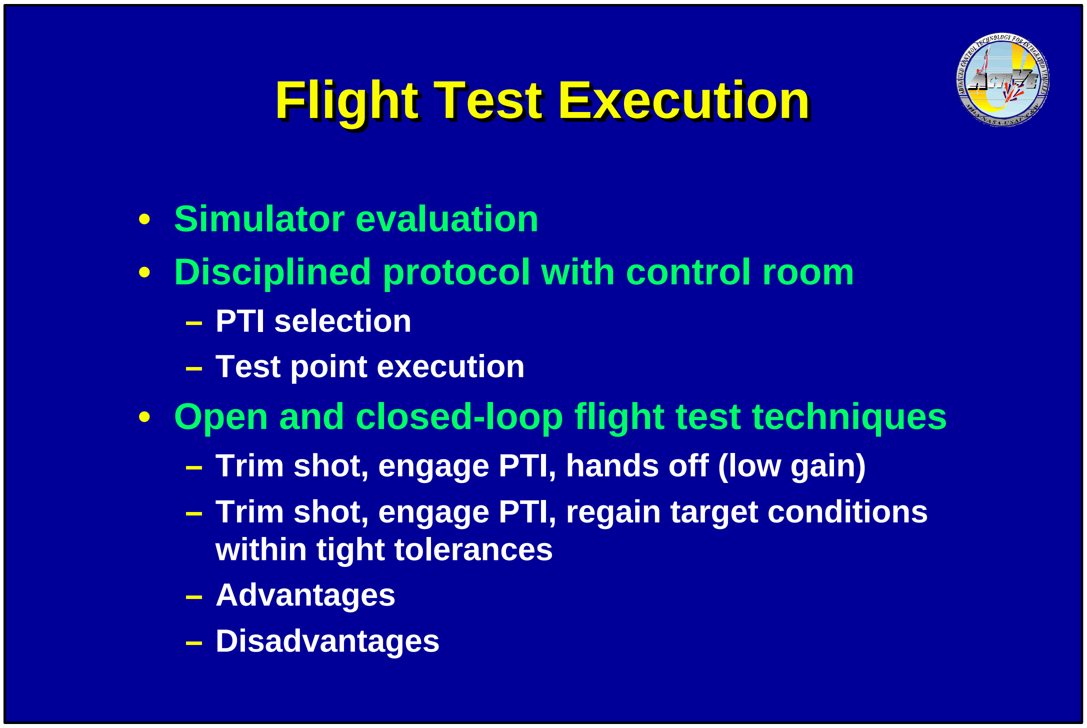

Before one of our project pilots could flight test an open loop DataSet, our mission rules required him to first execute the test point in the simulator. Not only did this improve efficiency for flight test, it more importantly allowed us a final check to ensure that the Programmable Test Input or PTI wouldn't break the jet.

We continued this conservative approach during flight test by making doubly sure that we didn't inadvertently engage the wrong DataSet. Prior to engaging the PTI, the control room had to give specific clearance to the pilot prior to selecting a DataSet. Additionally, parameters were reviewed and PTI selection was confirmed prior to clearance to commence the maneuver.

From a pilot's point of view, the flight test technique was fairly straight forward. We started off with a good trim shot, engaged the PTI, and then flew hands off the controls until several seconds after PTI completion. Most DataSets lasted only a few seconds, but a few were not complete for several minutes and required low gain control inputs to maintain "on conditions".

The PTI approach proved to be advantageous for our open loop phase. Inputs were crisper and more uniform than humanly possible. Additionally, numerous test points required perturbations that couldn't be accomplished with the controls available to the pilot. Finally, PTI decreased pilot workload and allowed the test pilot to concentrate on setup and data-band maintenance.

Disadvantages???????

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Video Placeholder

I have a short video to illustrate a typical pitch vectoring doublet from one of our flights. *(Roll video)*

The flight condition is ______________ (show 5 sec stabilized flight)

Here’s a close-up of the pitch doublet. (5 sec ground shot of pitch doublet)

The view from the chase aircraft (show 10 sec of vectoring flight)

The pilot’s perspective through the HUD (show 10 sec HUD video)

And the test conductor’s display during the pitch doublet. (Tim display)

EYEBALL MANEUVER

ANYTHING ELSE THAT IS NOTABLE (TBD)

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Nozzle Expansion Results

- Cumulative nozzle usage through flight 33
  - 42 total flight hours per nozzle
  - 4800 vector cycles
  - 210 minutes of total vectoring time
  - Over 11000 power cycles per engine

Obtained highest speed vectoring in aviation history (M=2.0)

This slide summarizes the cumulative usage of the vectoring nozzles through flight 33, our last flight, flown this past December. Of the 42 total flight hours, 3 and a half hours were spent vectoring with a total of 4800 vector cycles. Each engine experienced over 11000 power cycles during the 33 flights. This gives a qualitative feel for the number of aerothermodynamic loading cycles that the nozzles were subject to.

On flight 28, the ACTIVE F-15 obtained what is believed to be the highest speed vectoring in aviation history at just several one-hundredths under Mach 2 at an altitude of 45K ft. The nozzle controller drove the vector angle to its allowable limits in both pitch and yaw at that condition.

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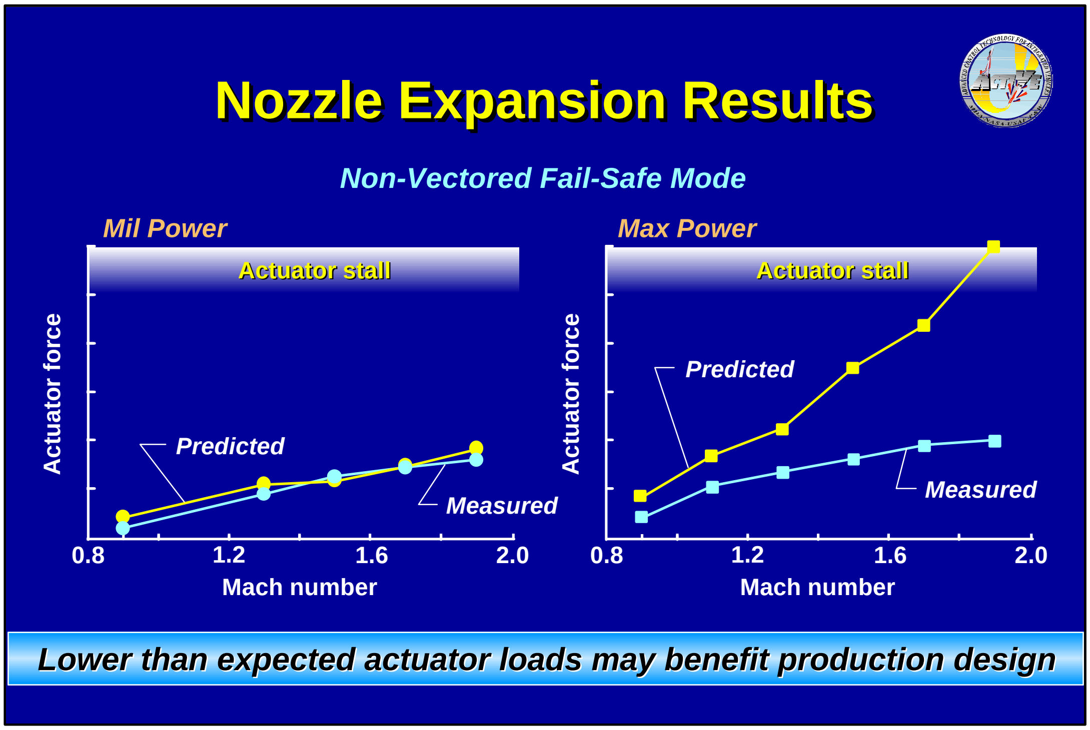


Much has been learned about the vectoring nozzle system since the ACTIVE program began. One surprise came in the area of nozzle structural loads, as manifested in the load measurements made on the divergent actuators.

The chart on the left shows predicted versus measured actuator load for a level deceleration at Mil power from Mach 1.9 at about 30K ft. The nozzles were in the locked fail-safe position. As can be seen, the two curves agree closely. However, for a Max power acceleration at the same altitude, the measured actuator loads were much lower than predicted as the figure on the right shows. In fact, the Max power actuator loading was only slightly higher than at Mil power.

This was a phenomenon seen throughout the flight envelope and may indicate that the nozzle structure has a higher factor of safety than originally designed for. These findings may benefit a production system by allowing an even lighter weight, lower cost design.

Nozzle Expansion Results

- **Operability summary**
  - **No dynamic flow instabilities**
  - **Very good thermal characteristics**
  - **Acceptable engine stall margin loss during vectoring**
  - **Adequate load factor-of-safety at all times**
  - **Safe, conservative operation of nozzle control vector load limiting and fault detection/accommodation logic**
  - **Nozzle seal-centering hardware redesign in-work; no other wear issues**

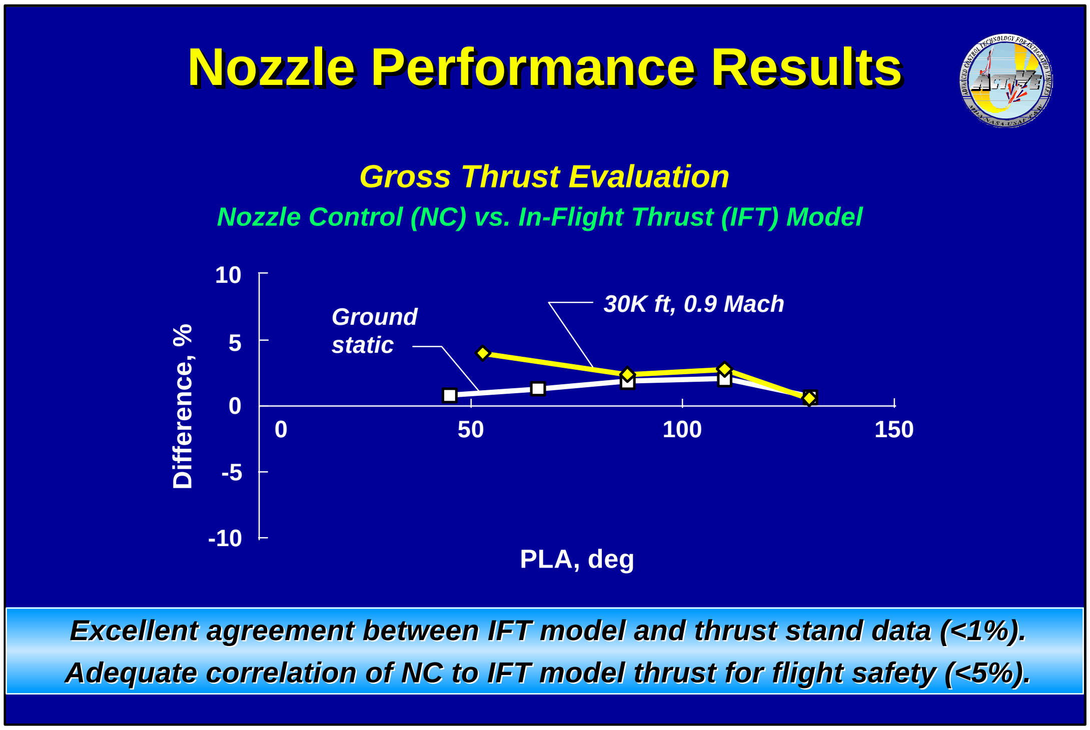
Safe and reliable operation throughout flight program

This list presents a summary of the results seen during the envelope expansion of the vectoring system. The nozzle has demonstrated stable flow throughout the program, and has shown very good thermal characteristics, with no scorching of the hardware or blow-by between the flaps and seals. Engine stall margin loss resulting from vectoring has been within acceptable limits throughout the flight envelope.

As mentioned on the previous slide, a greater than expected load factor-of-safety exists for the nozzle divergent actuators and structure. The nozzle controller never permitted the nozzle to produce an unsafe vectoring force. Vector forces have been less than predicted throughout much of the flight envelope because the vectoring effectiveness has been less than expected (explained in more detail on a forthcoming slide). A nozzle controller software re-design, with scheduling now based on flight data collected during the previous phase, is in progress. The new software will allow larger vector angles to be obtained, permitting the nozzles to produce vector forces closer to the target flight test limits. A full-envelope demonstration of the new system is planned for later this year.

The only in-flight wear issue seen with the hardware has involved the nozzle seal-centering mechanism. At the very large throat areas seen at Mach 2, the hardware experienced binding that resulted in minor bending of the divergent flaps. A re-design is in progress that will eliminate the binding, and will be demonstrated during the next phase. Otherwise, the hardware has been very robust.

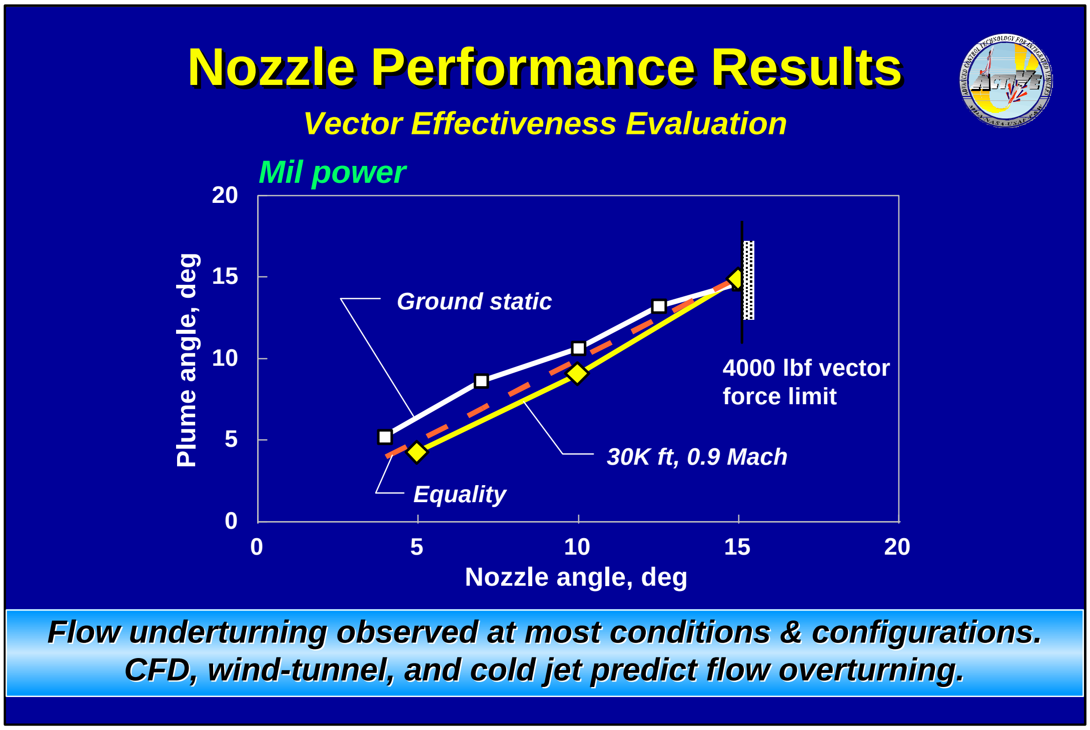
To summarize, the nozzles have exhibited safe and reliable operation throughout the flight test program.



One key objective of the nozzle performance research was to evaluate engine gross thrust predictions. An accurate gross thrust estimate is necessary to maintain adequate vector load safety margins and to assess vectoring performance benefits. Because the engine gross thrust cannot be directly measured in-flight, the aircraft-mounted Nozzle Control (NC) computer uses a simplified thrust model to provide a real-time estimate of gross thrust. The NC gross thrust estimate was compared with a higher fidelity off-line model, referred to as the In-Flight Thrust (IFT) model.

Before using the IFT-predicted gross thrust as a basis for comparison, however, the IFT model accuracy was assessed from a specially designed ground test where the aircraft was mounted to a thrust stand and gross thrust was directly measured. Results of this test indicated excellent agreement between the thrust stand and the IFT gross thrust, to within an average of less than 1 percent difference.

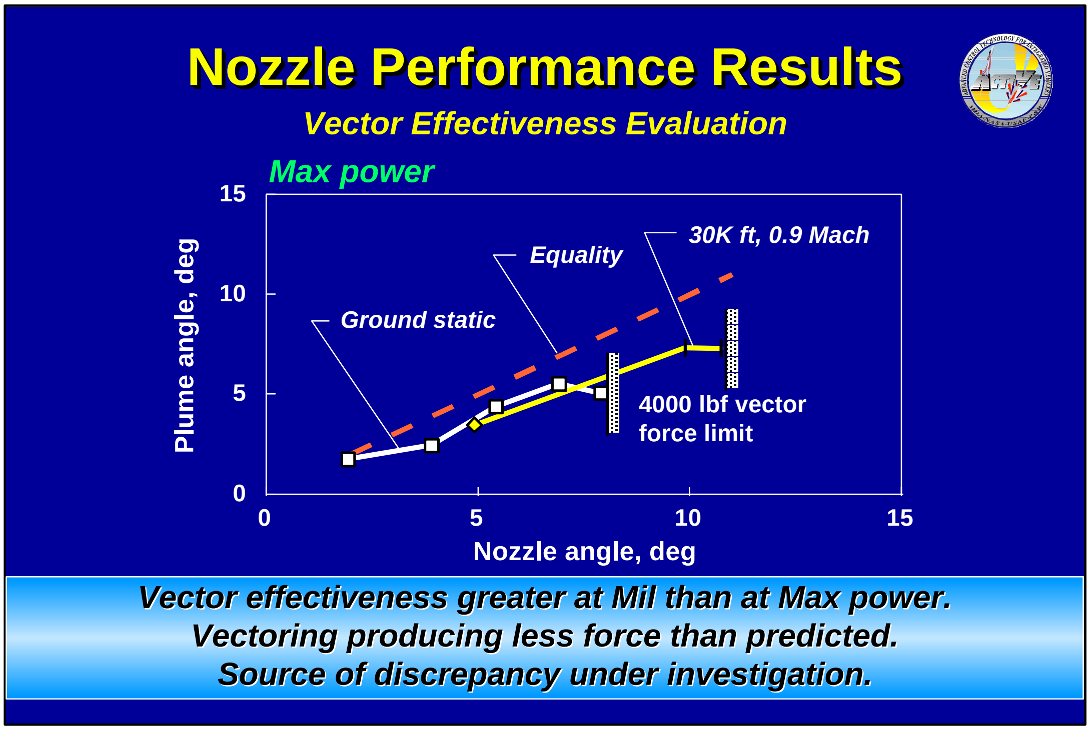
This slide shows the percentage difference between NC- and IFT- predicted gross thrust for two conditions as a function of power setting. Overall the results demonstrate the NC easily matches the IFT to within 5 percent or better for all power settings. Better agreement exists on the ground at static conditions than at the up and away flight condition of Mach 0.9 and 30000 feet. At up and away conditions, uncertainty in the NC model increases because it must account for additional terms such as inlet drag and recovery.



One measure of nozzle vectoring efficiency is its ability to turn the engine exhaust from a purely axial flow with no vectoring component to a vectored flow where some flow is directed off of the engine centerline. Flow turning is accomplished by rotating the divergent section of the convergent-divergent nozzle and may be measured in degrees from the engine centerline. The degree to which the exhaust flow follows the angle of the nozzle hardware is refereed to as the vector effectiveness. For example, a measure of 100 percent vector effectiveness is attained when the flow or plume angle matches the nozzle angle.

Plume and nozzle angles are cross-plotted to illustrate the measured vector effectiveness of data gathered at Mil power and two conditions. The dashed line represents 100 percent vector effectiveness for reference. Angles greater than about 15 degrees were not possible because of load considerations and a 4000 pound vector force limit.

The vector effectiveness at ground static conditions is greater than 100 percent and indicates the flow is being turned beyond the nozzle angle. The amount of flow overturning diminishes with increasing nozzle angle until 100 percent vector effectiveness is achieved at 15 degrees nozzle angle. At the up and away flight condition, the plume angle more closely matches the nozzle angle and vector effectiveness is reduced to just less than 100 percent. The variance in vector effectiveness results between the ground and flight conditions may be the consequence of substantially different flow properties, such as supply pressure and temperature, or differences of nozzle geometry.



Results from an evaluation of vector effectiveness at Maximum power are shown on this slide. Because of the higher thrust levels at Max power, the angle required to achieve 4000 pounds vector force is less than what it was for Mil power, and thus only about 8 and 11 degrees of nozzle angle were attained before being limited.

At both ground and flight conditions, vector effectiveness at Max power is much less than 100 percent and less than what was seen for the Mil power results. Also, the trend of diminishing vector effectiveness with increasing nozzle angle is present. Previous studies, subscale tests and analytical models, of vector effectiveness with nozzles of similar configuration have predicted flow overturning for most conditions. Associated with the reduced vector effectiveness, vector forces have also been measured and found to be less than expected.

At this stage of ACTIVE flight test vector effectiveness data have been gathered for only a small portion of the envelope and only preliminary assessments can be made. With additional testing and instrumentation it may be possible to isolate the primary influences on vector effectiveness. A more thorough explanation of the vector effectiveness trends is currently being researched in both flight testing, subscale testing and in reviewing analytical predictions and subscale testing.

Conclusions

- Nozzle hardware design proven
  - Safe operation throughout flight program
  - Peak non-vectored loads lower than predicted
- Nozzle control software design proven
  - Conservative operation of load limiting and fault detection/accommodation algorithms
- Nozzle performance
  - Flow underturning observed at most conditions
  - Vector effectiveness greater at Mil than at Max

The axisymmetric pitch-yaw balanced beam vectoring nozzles have been demonstrated throughout most of the flight envelope of the ACTIVE aircraft at speeds up to Mach 2.

The nozzle hardware has proven to be very robust. Binding seen in the seal-centering hardware will be corrected by phase 3. Peak divergent actuator and structure loads have been significantly less than predicted.

The nozzle control software load limiting logic was more conservative than expected in limiting the maximum vector forces. A software redesign will be implemented in the next phase to allow peak vector forces closer to the allowable limits.

Nozzle performance testing is on-going and at this point only preliminary nozzle performance data have been gathered at select flight conditions. The nozzle control model produced excellent predictions of gross thrust. Nozzle performance predictions were seen to be substantially different from measured nozzle performance over most of the flight and vectoring envelope. Further nozzle performance testing will be done with the redesigned nozzle control software to evaluate the full potential of the thrust vectoring system.

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Lessons Learned

- **Flexible open-loop test mode implementation critical to expansion success**
- **Simulation required for safety-of-flight assessment and maneuver definition, but is not the final answer**
- **Software limits, envelope limits, and maneuver restrictions must be collectively weighed to ensure flight safety**

Three significant lessons learned have come from the program to date.

1) Without the powerful open-loop test capability, envelope expansion could not have proceeded as efficiently and effectively as planned. Additionally, gathering force, moment, temperature, and pressure data during precise nozzle geometry configurations tests has produced results that lend insight into how all basic convergent-divergent nozzles perform.

2) Pilot-in-the-loop simulation was used extensively for DataSet definition, verification and validation, mission planning, and pilot flight test technique development. Although every effort was made to ensure that the models were of the highest fidelity, significant differences were encountered, especially in the vector force. Luckily, the simulation was conservative, but it could have been otherwise. Extensive simulation work lulls the team into expecting a certain aircraft response. The flight test process is a process of discovery and we always need to be alert for the unexpected.

3) The last lesson learned relates to results uncovered during our first hardware-in-the-loop simulation, where we learned that the extensive automated software limiting system designed to protect the aircraft from all hazardous test input commands, fell short. As a result, we developed a combination of envelope and maneuver limits to augment the software limiting system to ensure flight safety. In hindsight, the belief that a software system can protect the aircraft under all circumstances, generates a false sense of security and a reduced level of readiness, which, in turn, can lead to an incident. By understanding and routinely reviewing the limitations of the software system, and defining appropriate envelope and maneuver limits, a research test program can be accomplished safely and successfully.

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